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ERRORS IN MEASUREMENT OF UNDERWATER IRRADIANCE IN THE SEA

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Measurements of the level of irradiance created by daylight in the sea have become quite common. These measurement are a part of programs of study of hydrooptical characteristics of the sea, and also accompany many biological, geological and hydrological studies. Due to the great variety of conditions under which the observations must be performed, problems of accuracy and the selection of the most effective methods for massive measurements are of great importance. This work presents an attempt to summarize some of the experience of practical measurements of underwater irradiance performed at the Institute of Oceanography imeni P. P. Shirshov, Academy of Sciences USSR, to estimate permissible errors and to formulate certain recommendations for the most effective methods of measurement. /104

In most cases, values of underwater irradiance "from above" $E_1(z)$ and "from below" $E_2(z)$ are measured at level z [1], then expressed through the intensity $J(\theta, \phi, z)$ of the light field in the sea (z axis directed vertically downward, θ is the angle between the z axis and the direction in question, ϕ is the azimuth):

$$E_1(z)=\int_0^{2\pi} d\varphi \int_0^{\frac{\pi}{2}} J(\theta, \varphi, z)\cos\theta, \sin\theta\, d\theta;$$

$$E_2(z)=-\int_0^{2\pi} d\varphi \int_{\frac{\pi}{2}}^{\pi} J(\theta, \varphi, z)\cos\theta\sin\theta\, d\theta. \quad (1)$$

Sometimes the spatial irradiance $\varepsilon(z)$ is measured

$$\varepsilon(z)=\int_0^{2\pi} d\varphi \int_0^{\pi} J(\theta,\ \varphi,\ z)\sin\theta\, d\theta. \qquad (2)$$

At the same time, the irradiance of the surface of the sea E_0 is measured by a receptor located on the deck of the ship. The results of these measurements can be used to determine a number of quantities utilized in theoretical calculations -- the vertical attenuation factor α, local values of this factor for the given level z

$$\alpha_z=-\frac{1}{E_1(z)}\frac{\partial E_1(z)}{\partial z}, \qquad (3)$$

and values averaged over the sector $(z_1 - z_2)$: /105

$$\bar{\alpha}_{z_1-z_2}=\frac{1}{z_2-z_1}\lg\left[\frac{E_1(z_1)}{E_1(z_2)}\cdot\frac{E_{02}}{E_{01}}\right], \qquad (3a)$$

where E_{01} and E_{02} are the irradiance values of the sea surface E_0 at the moments when the device was located at levels z_1 and z_2.

The diffuse reflection factor of the sea ζ is also calculated

$$\zeta(z)=\frac{E_2(z)}{E_1(z)} \qquad (4)$$

as well as the underwater irradiance factor η

$$\eta=\frac{E_1(z)}{E_{01}}. \qquad (5)$$

Furthermore, the values of $E_1(z)$, $E_2(z)$ and $\varepsilon(z)$ are used to calculate the absorption factor [2]

$$\varkappa(z)=\alpha(z)\left[1-\zeta(z)+\frac{\zeta'(z)}{\alpha(z)}\right]\frac{E_1(z)}{\varepsilon(z)}. \qquad (6)$$

Obviously, errors in these calculated quantities are determined, in the final analysis, by errors in measurement of the values of underwater irradiance.

Errors in measurement of underwater irradiance are determined by a large number of factors, many of which are not considered in measurement practice. It is expedient to combine the factors influencing the accuracy of measurement of underwater irradiance and the quantities calculated from irradiance into the following groups:

a) errors related to instability of the sensor of the device and calibration errors;

b) errors determined by the geometry of the device and its design peculiarities;

c) influence of errors in determination of depth on accuracy of calculation;

d) errors related to the methods of recording and processing of data produced.

Let us study the errors of each group of factors individually.

Errors related to errors in calibration and sensor instability. Underwater irridance is most frequently measured using selenium photocells, preferred because of the simplicity of their use, their relative stability and satisfactory sensitivity. In this case, the primary sources of errors include errors in calibration of the device and errors resulting from fatigue and aging of the photocell.

Calibration errors. Calibration of photocells in a well- /105
equipped photometric laboratory can produce measurements of cell sensitivity in absolute units with accuracies of not over 5%, which is determined by the accuracy of standardization of the light source used in calibration[1]. Thus, the upper limit of

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[1]Correct calibration of the device for measurement of underwater irradiance assumes the presence of a thin layer of water on the surface of the device. This is necessary in order to consider the influence of the immersion effect [4].

accuracy of measurement of the absolute value of irradiance in spectral intervals near the maximum of spectral sensitivity of the photocell is ±5%.

In the process of measurement using this photocell, this error is systematic and decreases upon calculation of relative quantities [3-6], which are generally of the greatest interest. In this case, the accuracy of the relative quantities produced is determined by the linearity of the light characteristic of the photocell. Our experience has shown that for this type of determination, the relative error is on the order of 3% of the maximum value of the measured quantity.

Fatigue of selenium photocells. When a selenium photocell is struck by sufficiently intense light, reversible reduction of its sensitivity occurs. Usually, fatigue is not observed in selenium photocells when they are struck with blue or green light with intensities at the surface of the photocell corresponding to up to 100-200 lx; with red light, fatigue begins considerably earlier. The fatigue properties must be tested for each photocell in a device in the ranges of irradiance used in each spectral interval. The checks must be performed systematically, since the fatigue properties may change during extended use. In order to reduce the irradiance on the surface of the photocell to a permissible level, devices usually have several neutral light filters of various densities. Attempts to expand the measurement range of the device by means of an electrical shunt are forbidden.

Aging of photocells. During long operation, selenium photocells change their sensitivity irreversibly. The curve of spectral sensitivity of the photocell changes noticeably. Most frequently, the maximum of sensitivity is shifted toward the violet end of the spectrum, with a general reduction in sensitivity. The aging rate of photocells depends on their operating conditions (irradiance, temperature and humidity, etc.) and varies quite strongly from photocell to photocell. This makes it necessary to check the sensitivity of selenium photocells over the entire

spectrum regularly (at least once per month), using a test light /107
source and the light filters installed in the device. Unnecessary exposure of photocells connected in the circuit to bright light is forbidden.

Errors determined by the geometry of the device and its design peculiarities. Let us study the influence of the most significant factors.

Deviation of the angular sensitivity function of the receiver from the cosine rule (or, by analogy, for a spherical receiver -- deviations from isotropicity).

In order to check the error resulting from deviation of the sensitivity of the receiver from the cosine rule, we must measure the angular sensitivity function of the receiver $\zeta(\theta)$ (assuming $\zeta(0) = 1$) during calibration of the device, and must also know the angular distribution of radiation in the sea $J(\theta, \phi, z)$. For level z, the relative error is

$$\frac{\Delta E_1}{E_1} = \left[\frac{\int_0^{2\pi} d\varphi \int_0^{\pi} J(\theta, \varphi, z) \zeta(\theta) \sin \theta \, d\theta}{\int_0^{2\pi} d\varphi \int_0^{\pi} J(\theta, \varphi, z) \cos \theta \sin \theta \, d\theta} - 1 \right] \cdot 100\%. \quad (7)$$

Calculations performed using values of angular sensitivity function $\zeta(\theta)$ on the FMPO-60 device [1, 3] and dependence $J(\theta, \phi, z)$ [5] for the subsurface level (where the radiation is directed) and a deep level (where the radiation is diffuse) have indicated maximum values of relative error of 5 and 4% respectively. Thus, the difference in error values even for the limiting cases is not over 1%.

For a spherical receiver, the deviations from isotropicity (with good quality scattering sphere) are determined by shading of a portion of the sphere with the body of the instrument and mounting parts holding the scattering sphere to the device. In particular, for the FMPO-64 device with attachment, the relative error is near 8% in a light mode similar to the deep sea light mode. As we can see, the relative deviations are quite similar for different types of illumination (in the subsurface mode and deep mode). This allows a single constant correction to be used for calculations for each light collector of this device. Knowing function $\zeta(\theta)$ of the receiver, we can calculate this correction. Thus, consideration of deviation of the sensitivity of the device from the cosine rule or from isotropicity is reduced to addition of the calculated correction. With proper use of this correction, the error due to deviation of the angular sensitivity of the device from the cosine rule will not exceed ±1%.

Errors related to errors in determination of effective /108
density of neutral light filters. As was noted above, in order to allow a selenium photocell to operate over a broad interval of irradiance, neutral light filters must be used, usually placed between the receiving collector and the photosensor. Since the neutral light filter attenuates more or less scattered light (degree of scattering depends on the nature of distribution of radiation and quality of ground glass in scattering element), the effective density of the filter must be determined directly in the instrument.

The procedure for determination of the effective density of neutral filters over a broad range provides low accuracy (not over 10%); therefore, absolute values of illumination levels measured with neutral filters (particularly dense filters) contain significant errors. There errors, determined for each device, are systematic errors, difficult in practice to consider. Therefore, absolute measurements of high levels of irradiance have errors of at least 10%. According to formulas (3)-(6), the error in determination of the density of a neutral light filter is obviously insignificant when data produced with the same neutral light filter are used. Otherwise, the error in determination of effective densities cannot be eliminated. Thus must be considered in processing experimental data.

Errors related to nonmonochromatic nature of color light filters. As natural light propagates through the sea, its spectral composition is significantly changed. Therefore, if a sufficiently broad light filter is used to measure underwater irradiance, as the depth of the device changes, the effective wavelength of transmission of the filter also changes and, in practice, the irradiance is measured at each depth in a different range of the spectrum. The transmission band of the light filter is effectively shifted in the direction of the maximum of transmission of sea water, increasing the values of irradiance for measurements in the spectral areas near the ends of the visible light range.

Thus, the nonmonochromatic nature of light filters effectively smooths the curve of spectral distribution of radiation. The errors resulting from this effect can be avoided by considering λ_{eff} for each filter, considering the spectral distribution of irradiance at each given depth.

Error resulting from deflection of optical axis during underwater measurements. During measurements in the sea, the device is practically always more or less tilted (which may result from /109 tilting of the supporting cable during drifting or from incomplete balancing of the instrument). The errors in values of E_1, E_2 and ζ for various angles of inclination of the device to the vertical ψ are presented in Table 1, as determined by analysis of experimental values of the illumination under the actual surface of the sea in the plane of the sun with a sun height of 50-60° over the horizon. There the superscript "m" is used to mark measured values; those values without superscript are the true values.

TABLE 1

ψ, deg	E_1^m/E_1	E_2^m/E_2	ζ^m/ζ
0°	1.00	1.00	1.00
5	0.92	1.05	1.16
10	0.81	1.06	1.32
15	0.72	1.08	1.51

Table 1 shows that during measurements of underwater irradiance the tilt of the instrument should not exceed 5°.

After determining the tilt angle of the device during measurements, one must calculate the correction to the measured value of underwater irradiance; after introduction of the correction, the error in the value of E_1 can be estimated as ±2% of the measured quantity.

Error in measured irradiance resulting from error in determination of depth of device. Relationship (3) yields the relationship between error in determination of depth Δz and resulting error ΔE_1 in irradiance

$$\frac{\Delta E_1}{E_1} = -\alpha_{\Delta z}.$$

Assuming that the error in depth of the instrument, determined from the length of the supporting line, is approximately 1 meter (at 100-150 meters depth) we produce for pure ocean water the approximate value $\Delta E_1/E_1 = \pm 0.06$.

The errors related to the method of data recording used can be estimated basically from the class of accuracy of the device. When operating in the central portion of the scale of a measuring device of class 0.5, the relative error lies within ±1%. We must note the following factor. When underwater irradiance is measured at slight depths, even light wave action on the surface (level 1 or 2) causes the instantaneous values of irradiance at level z to fluctuate strongly. When a selenium photosensor is connected to an indicator device such as a type M-194 microammeter, the light spot of the ammeter moves over a wide portion of the scale. Average values are frequently taken "by eye," which naturally results in significant errors. In order to measure the underwater irradiance at slight depths, it is desirable to average the instantaneous values of irradiance; in particular, we recommend the use of an RC circuit, acting as a damper, connected between /110 the photocell and electrical measuring (indicating or recording) device. With a time constant of 5-10 sec, the fluctuations in indications of the device will remain within 0.5 to 1 scale division of the device.

All of the primary sources of error in the determination of underwater irradiance listed above and the greatest values of these errors are presented in Table 2.

TABLE 2

Error Source	Limiting Values of Error in Measurement, %	
	E_1	$E_1(z_1)/E_1(z_2)$
Calibration	±5	±3
Deviation of angular sensitivity from cosine rule .	±1	--
Neutral light filter	±10	--
Drift of axis of device from vertical	±2	--
Imprecise placement of device at assigned depth .	±6	±6
Accuracy of indicator	±1	±2

We note that many of the errors involved in determination of $E_1(z_1)/E_1(z_2)$ become very slight, so that we can ignore their values; these include the errors resulting from deviation of the angular pattern of the receiver from the cosine rule, from inaccurate knowledge of the transmission factor of a neutral filter (assuming that the readings at levels z_1 and z_2 are taken with the same neutral filter) and errors resulting from deviation of the angle of the receiver from the vertical, since this angle will change only slightly if levels z_1 and z_2 are close together. The error resulting from inaccurate calibration of the photocell also decreases significantly.

We must now note the following facts:

a) All of the sources of error indicated in Table 2 are independent of each other;

b) Each error is positive or negative with equal probability; /111

c) These errors (except for the last in Table 2) have a dual nature: for a given device in a given series of measurements (meaning measurements at a single station in the course of one to two hours), all of these errors repeat in magnitude and sign, i.e., are systematic. In this case, the resulting error cannot be decreased by simple repetition of measurements;

d) However, if we consider the entire set of devices of a given type used for measurement of underwater irradiance and utilizing selenium photocells covered with neutral light filters, calibrated at different times using different photometric lamps, and also if we take all the results of measurement using these devices at different times under different weather conditions, the errors will be random errors and, due to the independence of each other, the total error produced will be the square root of the sum of squares of the components σ_i:

$$\sigma=\sqrt{\sum_{i=1}^{n}\sigma_i^2},$$

where n is the number of these components. The value of error determined in this manner for the entire set can be called the error of an instrument of this type; in our case, this error is 12-14% for absolute measurements of E_1 and 7% for the ratios $E_1(z_1)/E_1(z_2)$.

It should be emphasized once more that these values of error can relate only to those measurements in which all of the cautionary statements presented above were observed carefully and the required corrections were used religeously. Therefore, much of the data produced in previous years on values of underwater irradiance does not satisfy these values of relative error.

Let us study the question of the expediency of performing several probings of the sea using an irradiance sensor during a

single series of measurements, in order to decrease random error. It was noted above that for a single series of measurements, certain sources of errors will give repeated similar values of error; in total, they form the constant error. However, errors of purely random nature also arise during measurements: errors in taking readings from devices, dispersions in true depth of the device with the same assigned depth, etc. The random errors of one /112
series can be determined from the data of several soundings. For example, 8 soundings of the sea which we performed in sequence using the FMPO-64 device under constant weather conditions indicated that the mean square random error of one measurement was 4%.

Comparing this figure with the error values of 12-14% and 7% presented above, we can conclude that in measurements of underwater irradiance using devices such as the FMPO-64, repeated soundings are hardly expedient, since they cannot lead to any significant increase in measurement accuracy.

Finally, it is quite important to select the optimal value of step Δz between points at which values of underwater irradiance are measured. To produce this estimate, one should first determine the purpose of the measurement. If E_1, E_2 and h are to be measured in order to calculate the mean values of α or κ for the layers, these estimates can be produced from expression (3a)

$$\Delta\alpha=\frac{1}{z_2-z_1}\left[\frac{\Delta E_1(z_1)}{E_1(z_1)}+\frac{\Delta E_1(z_2)}{E_1(z_2)}\right]. \tag{8}$$

Since the relative error $\Delta E/E_1$ is approximately the same at all levels where measurements are made, we can write

$$d\alpha=\frac{2}{z_2-z_1}\cdot\frac{\Delta E}{E_1}. \tag{9}$$

We can see from this that increasing the step in making readings $z_2 - z_1$ can reduce the error in determination of α to a very small quantity. However, we must recall that in this case the value of α produced has the sense of a mean for a layer of thickness $z_2 - z_1$; thus, by increasing the step too greatly, we lose information on the fine variation of α with depth.

We recommend that measurements be made with a depth step Δz such that the values of irradiance change by a factor of 3 to 4 between measurement points. The measurement procedure consists in lowering the device after each reading to the level where this relationship is achieved. However, one should not forget the requirement of standardization of measurements; the reading levels should at least be multiples of 5, 10 or 20 meters. Therefore, the optimal step as formulated above can be achieved only approximately. For example, in measurements in the Black Sea, where the decimal value of $\alpha = 0.05 m^{-1}$, we find the value of optimal step $z_2 - z_1 = 10$ m.

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